Unification of radar and sonar coverage modeling

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Abstract – Radar and sonar are by tradition separate disciplines with different user communities. This situation is about to change as many navies are experimenting with reduced manning concepts. As a result, tomorrow’s sensor operator is likely to monitor and control all available sensors on his own. In this situation operator overload is expected, especially due to less educated and less experienced personnel and the introduction of new and more complex sensor systems. A possible solution is a high level of automation in sensor management and the integration of tactical decision aids. To further assist the human operator, this work aims to unify sensor performance modeling for the complete sensor suite. The radar and sonar equations are compared and combined with a propagation model for complex environments. The analysis of a real-world scenario with both radar and sonar is shown to result in a unified visualization of predicted sensor coverage.

Keywords: Sensor performance, environment, propagation modeling, radar, sonar.

1 Introduction

For a long time the optimal deployment of naval sensor systems has been dependent on the skills and experience of human operators. In recent years several trends have emerged that shed a new light on the performance of naval sensing.

Firstly, western navies are experimenting with reduced manning concepts. Fewer people with less education are to do the same jobs. In the past, sailors were trained to become either a sonar operator or a radar operator. Today, one operator has to control both radar and sonar systems while he is expected to monitor his electro-optical sensors at the same time.

Secondly, the areas where NATO countries deploy their ships have shifted from open ocean to littoral waters. These coastal waters are often shallow (meaning less than 200 m water depth) and characterized by a continuously varying, and in general unpredictable, environment. In littoral areas it is harder to predict how well a sensor will perform than for open ocean environments. The physics, on the other hand, are well understood, and many computer programs have been written [1] that model the propagation of signals through various media. Environmentally adaptive sensing is a new skill that is making way within western navies [2].

A third trend is that new ships are fitted with new sensor systems. It is not only impossible to find experienced operators for new systems, the complexity has grown to such an extent that optimal sensor deployment by human operators has in some cases become an impossible task.

If there is any solution for these problems, we think it is in the design of a combat management system (CMS) that is smarter than previous generations of operational software. In a separate paper, we describe the framework and design of such a smart CMS [3].

This work is about sensor performance and proposes a unification of mathematical equations and data visualization. The motivation for such a harmonized approach in radar and sonar performance is that the operator will require less education, is likely to make fewer errors and will have a better understanding of how separate parameters influence the assessed sensor coverage.

2 Radar and sonar theory

Radar and sonar are separate disciplines with distinct user communities. Despite the physical differences between the two sensor types, some striking similarities can be noticed. In this article a comparison is made between (monostatic) radar and active sonar.

For sonar, the propagation of sound is bound to a medium. The speed of a sound wave fully depends on the medium density and compressibility. Radar waves propagate with the speed of light, even in a vacuum. However, the wave lengths of radar and sonar signals are of the same order of magnitude and so are the antenna sizes. For both sensor types the physics are well understood and mathematical equations that express the sensor performance are extensively documented [4, 5, 6, 7]. The corresponding variables are defined in following sections.
The radar range equation can be written [6] as
\[ R_{\text{max}}^4 = \frac{E_i G A \rho_a \sigma_n E_i(n)}{(4\pi)^2 k T_s (E/N_0)} L_s \] (1)
while the corresponding sonar equation is often stated [4] as
\[ SL - 2 TL + TS = NL - DI + DT \] (2)
which is the active sonar equation for the noise limited case.

The equations have a different appearance, but the latter one is expressed in decibels so that both equations are products of comparable parameters. The commonality can be found when the parameters are grouped according to the traditional decomposition in signal source, the medium and the receiver. In this work we will arrange the parameters differently and consider the terms sensor system, medium and target.

2.1 Sensor system parameters

Parameters from Equation 1 and 2 that describe radar and sonar systems are listed and compared in Tables 1 to 4. Besides the decibel notation for sonar, the key parameters are basically the same.

<table>
<thead>
<tr>
<th>Sonar</th>
<th>Radar</th>
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</thead>
<tbody>
<tr>
<td>Table 1: Transmitted signal</td>
<td></td>
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<tr>
<td>SL source level (dB)</td>
<td>( E_s = P_t \tau ) energy in transmitted pulse</td>
</tr>
<tr>
<td>= 170.8 + 10 \log P</td>
<td></td>
</tr>
<tr>
<td>( P ) power (watt)</td>
<td>( P_t ) power (watt)</td>
</tr>
<tr>
<td>( \tau ) pulse length (s)</td>
<td></td>
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</table>

Table 2: Antenna gain

<table>
<thead>
<tr>
<th>Sonar</th>
<th>Radar</th>
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</thead>
<tbody>
<tr>
<td>DI directivity index</td>
<td>( G ) antenna gain</td>
</tr>
<tr>
<td>( = 10 \log(2L/\lambda) ) (dB)</td>
<td>( = 4\pi \rho_a A/\lambda^2 )</td>
</tr>
<tr>
<td>( L ) length of array (m)</td>
<td>( A ) antenna aperture (m²)</td>
</tr>
<tr>
<td>( \lambda ) wavelength (m)</td>
<td>( \rho_a ) antenna efficiency</td>
</tr>
<tr>
<td>( \lambda ) wavelength (m)</td>
<td></td>
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</tbody>
</table>

From Table 2 it follows that the antenna gain in both sensor systems depends on sensor aperture and wavelength. The latter depends on the signal frequency \( f \) according to
\[ c = f \lambda \] (3)
where \( c \) is the speed of the wave in m/s, and not necessarily the speed of light. Notice that for radar we assume a monostatic system so that transmission and receiving gain are the same. For sonar the antenna gain for transmission is usually dealt with as part of \( SL \). This explains the different power of \( \lambda \). The signal-to-noise ratios from Table 3 describe the situation for the range where a signal can just be detected. For sensor performance modeling it is often more convenient to express the signal-to-noise ratio in terms of probability of detection \( p(D) \) and probability of false alarm \( p(FA) \):
\[ \frac{S}{N_0} = \frac{d}{2\tau} \] (4)
for a pulse with length \( \tau \) in s and \( d \) the receiving operating characteristic (ROC) according to
\[ d = \left[ \frac{\ln(p(FA))}{\ln(p(D))} - 1 \right]^2. \] (5)

Table 3: Detection characteristics

<table>
<thead>
<tr>
<th>Sonar</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT detection threshold ( 10 \log(S/N_0) ) (dB)</td>
<td>( E/N_0 ) signal-to-noise energy ratio</td>
</tr>
<tr>
<td>( S/N_0 ) signal-to-noise energy ratio ( n ) number of hits</td>
<td></td>
</tr>
<tr>
<td>( E_i(n) ) integration efficiency</td>
<td></td>
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</tbody>
</table>

A major difference between radar and sonar can be found in Table 4 where the dominant noise sources are listed. Sonar performance is very much dependent on the ambient noise which is an environmental condition. In radar, the noise is part of the sensor system and poses a far lesser constraint. To harmonize matters, all noise can be treated as a system parameter. For ambient noise, this harmonization is a bit of make-belief, but by definition, the parameter is quantified as measured at the receiver [4].

2.2 Medium parameters

When a signal propagates through a medium, the signal can be influenced by the medium. Sonar signals are usually strongly affected by the environment. Table 5 gives a rule of thumb [4] for sonar propagation loss (\( TL \)) that is valid for spherical spreading with attenuation due to absorption. Attenuation depends on the frequency and is often neglected for low frequencies, both for radar and sonar. In radar equation 1 the resulting loss of \( R^4 \) is essentially the same as in the sonar rule of thumb. The propagation loss in Table 5 is for simple cases. In more complex environments signals can be refracted, trapped in ducting layers, reflected, and even be received via multiple paths. For these cases, it is common to compute losses with a propagation model [1, 8, 9]. These computer models require environmental input such as bathymetry or altimetry, bottom properties, and weather...
Table 5: Propagation loss

<table>
<thead>
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<th>Radar</th>
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<tbody>
<tr>
<td>$2TL$ transmission loss (dB)</td>
<td>$R^4$ range (m)</td>
</tr>
<tr>
<td>$= 2(20 \log R + \alpha R)$</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ absorption (dB m$^{-1}$ kHz$^{-1}$)</td>
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</table>

conditions [2]. For radar, the use of a loss model results in a slight change of Equation 1.

### 2.3 Target parameters

Reflection parameters for targets are listed in Table 6. Regardless of unity, both reflection parameters are aspect angle dependent. Here we consider monostatic systems (source and receiver at the same position) so that reflection depends on a single bearing only. Target strength and radar cross sections can then be presented in a polar diagram that often takes the shape of a butterfly pattern. When the angle of detection is not known beforehand, an average reflection value can be used.

A difference between radar and sonar is the fluctuation of reflectivity parameters. The radar cross section is quite sensitive to aspect [6]. Small angular differences can result in major differences in reflection. The radar cross section is often determined by the average of many pulses, as expressed in Table 3. A common approach is then to obtain detection probability from one of the Swerling cases [7] that model the fluctuation in reflectivity. Fluctuation of sonar target strength is less sensitive to aspect than the radar cross section. Different than radar, sonar has a much longer dwelling time which is the result of much longer pulses and much lower speed of the signal (1500 m/s).

### 3 Decision support

The current work fits in the larger framework of automated management of sensor systems as presented by Bolderheij in [10]. In this framework, generic sensor tasks are distributed and scheduled over the available sensor systems. Information is therefore required about the performance of separate sensors for these tasks. In view of a supervised assessment of sensor performance, a system concept will be given of an online sensor performance component.

The making of (tactical) decisions is a predictive effort. For this reason the assessment of sensor coverage does not have to be a real-time process. It is merely an anytime effort in the sense that models are evaluated continuously and results are accessible when needed.

The setup of a sensor performance model requires the initiation of many parameters. Following the previous section on the radar and sonar equations, the input parameters can be assigned to the categories

1. sensor system,
2. environment, and
3. target (or contact of interest).

### 3.1 Scenario

The unified approach to radar and sonar coverage modeling is demonstrated in a simple scenario. A ship with radar and a helicopter with dipping sonar aim to establish a common operational picture. To support the effectiveness of the picture compilation process, it must be determined which area is covered by which sensor. In addition, for the helicopter, an optimal depth setting is required for the dipping sonar.

### 3.2 Sensor systems

The ship is equipped with a generic 3D volume search radar system that operates in the 1–4 GHz band. The helicopter lowers its low-frequency dipping sonar (1–2 kHz) to depths between 50 m and 250 m. Sonar performance will be evaluated at 50 m intervals.

The radar and sonar communities use different detection thresholds due to the different nature of the sensor systems. The threshold specifies a signal-to-noise ratio where detection depends on probabilities of detection and false alarm, as specified in Equation 4 and 5. The probabilities used here are common values [5, 7], and specified in Table 7. The radar and sonar in this scenario are both omni-directional in the sense that the antenna gain is the same for every bearing.

### 3.3 Environment

Both units are located at the same geographic position. For sonar modeling a bathymetry was taken from the public NOAA databases [11]. An area of 100 km by 100 km was selected near the coast of Somalia and centered at 12°N and 51.5°E. The gridded bathymetry has a resolution of 1 nm and was interpolated for the required range intervals. The sonar propagation loss was calculated with the range dependent loss model RAMgeo [1, 12]. Radar performance was calculated with the model CARPET [13] in a range independent mode.

<table>
<thead>
<tr>
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<th>Radar</th>
</tr>
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<tbody>
<tr>
<td>$p(D) = 5$</td>
<td>$p(D) = 0.95$</td>
</tr>
<tr>
<td>$p(F.A) = 0.005$</td>
<td>$p(F.A) = 1 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$f = 1.5$ kHz</td>
<td>$f = 3.3$ GHz</td>
</tr>
</tbody>
</table>
3.4 Target properties

The target, or contact of interest, is a medium sized surface ship. Reflectivity parameters are specified as: $TS = 15$ dB and $\sigma = 10 \text{ m}^2$. In practice, reflectivity depends on the aspect angle and at short range also on elevation. In this scenario some settings were simplified, e.g., reflectivity parameters were chosen to be independent of aspect angle.

4 Results and visualization

Sensor performance was evaluated with Equation 1 and 2. The resulting probabilities of detection are mapped in Figure 1 and 2, and can be used as overlays on a sea chart.

4.1 Individual visualization

Probabilities in Figure 1 and 2 are mapped into a unified color scheme, according to [14]. The threshold, that marks a ‘good’ detection, differs for radar and sonar. The colors red and yellow represent ‘good’ detection, which is $p(D) > 0.5$ for sonar and $p(D) > 0.95$ for radar.

A comparison of Figure 1 and 2 shows that sonar has a more extended coverage in the northeastern region. The performance of the sonar system strongly depends on the bottom contours and is limited towards the south region with a detection range of 9 km for $p(D) > 0.5$. The radar has a high probability of detection ($> 0.95$) in all directions and up to the radar horizon at 20 km. Beyond that range the sonar system may still detect a target in the northeastern region.

4.2 Unified visualization

This work is driven by the integration of tactical decision aids into the combat management system. Apart from automated data streams and unified color schemes, the workload of the operator can be reduced by fusing the most important sensor coverage information into a few displays.

4.2.1 Height and depth versus range

Figure 3 demonstrates a combined display for the coverage of air (volume search radar), underwater (sonar), and the water surface (both sensors). The same color scheme is used as in Figure 1 and 2. The pictured slider-controls on the right are an example of human-machine-interfacing (HMI). The slider controls height and depth settings for the sensors and these parameters are input for Figure 1 and 2. Likewise, displays based on Figure 1 and 2 could have controls to determine the bearing, which is the input for Figure 3.

4.2.2 Combined bird’s eye view

Figure 4 displays data from all sensors and settings that were evaluated. A different color scheme is used: a color represents the radar (red) or the sonar with a specific depth setting (other). Notice that for paper print, the colors in Figure 3 are chosen to fade to white. On a computer display the colors could be transparent or fade to black instead.

From Figure 4a it follows that the optimal depth setting for the dipping sonar is 50 m for long range detection and 250 m for short range detection. When radar and sonar are deployed, Figure 4b shows that the radar has the highest probability of detection in all bearings and up to 20 km. Beyond the horizon the sonar is likely to make detections in...
Figure 3: Combined display for probability of detection for radar (upper half) and sonar (lower half). The pictured slider-controls on the right are an example on how to control the height and depth settings that are input for Figure 1 and 2. Likewise Figure 1 and 2 could have controls to determine the bearing that was input for Figure 3.

Figure 4: Combined probability of detection for sonar and radar. The left diagram (a) is for sonar coverage only, and plots the color for the setting with the highest probability of detection. The right diagram (b) also includes the radar coverage (red).
the Northeastern region. All this information is presented in one display.

5 Discussion
In this work the modeling and visualization of radar and sonar performance has been demonstrated for a simple scenario. The proposed unification of mathematical equations and data visualization does not change for scenarios that are much more complex.

Radar and sonar performance were shown to depend on similar parameters, even though the common values can be quite different. Harmonization of performance equations is not limited to the radar range equation and the active noise-limited sonar equation. Reverberation [4, 5] and clutter [6, 7] are equal concepts that can be modeled in a unified approach. Also, passive intercept sonar [4, 5] and electronic support systems [6, 7] are assessed by very similar equations. The unified approach is no different for signature management and predictions of counter detection ranges. Further unification between radar and sonar modeling appears to be very well possible.

A remarkable difference between radar and sonar is the appreciation of a good detection in terms of probabilities of detection and false alarm. It is an option to define a new standard for probabilities of detection and false alarm that defines ‘good’ and ‘bad’ performance. In this work we replaced sensor-dependent probabilities by four general categories that could be labeled as excellent, good, moderate, and bad.

Unification and fusion of sensor coverage diagrams was shown in figures 1 to 4. By presenting the most important information in a unified manner, and in just a few diagrams, the operator does not have to compare sensor coverage: the system can make the comparison for him. Unified human machine interfacing enables operators to easily switch between displays for radar and sonar performance. The proposed unification can compensate for shortage of limited available personnel, provide backup for lack of experience and education, and provide a better understanding of how separate parameters influence the assessed sensor coverage.

6 Conclusion
This work fits in a larger framework of operational software, such as combat management systems. In the context of sensor management, sensor performance is likely to be an input for sensor allocation. The proposed unification of sensor performance modeling is aimed to reduce the amount of information that the multi-sensor operator has to process. Unified modeling and fused visualization of sensor coverage has been demonstrated for radar and sonar in a simple scenario. The radar range equation and the active sonar equation initially look completely different but have been shown to be nearly identical. The input parameters of any sensor system can be set according to a unified structure that fits to human perception of a sensor system. By replacement of sensor-specific displays by unified displays, the operator is provided with insight about the performance of the complete sensor suite.

References